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WEB CRIPPLING BEHAVIOUR OF COLD-FORMED UNLIPPED CHANNELS

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ABSTRACT

An experimental investigation of cold-formed unlipped channels subject to web crippling is described. The tests were carried out under four loading conditions according to the AISI Specification, namely End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF), and Interior-Two-Flange (ITF) loading. The concentrated load or reaction forces were applied by means of bearing plates which acted across the full flange widths of the channels. The web crippling test results are compared with the American Iron and Steel Institute (AISI 1996) Specification and the Australian/New Zealand Standard (AS/NZS 4600-1996) for cold-formed steel structures. The design web crippling strength predictions given by the specifications have been found to be very unconservative for the unlipped channel sections tested. In this paper, simple plastic mechanism formulae for web crippling strength of unlipped channels are proposed.

1 INTRODUCTION

In thin-walled steel construction, transverse and shear stiffeners are often difficult and uneconomical to install. In the absence of stiffeners, the webs of thin-walled beams composed of open sections may cripple due to high localised bearing forces. Therefore, web crippling (bearing failure) must be accounted for in the design of cold-formed steel members. However, theoretical analysis of web crippling for cold-formed members is complicated due to a number of factors (Yu 1991), such as elastic and inelastic stability of the web element, local yielding in the immediate region of load application, initial imperfections of plate elements and other factors. Thus, the design recommendations to prevent web crippling contained in the American Iron and Steel Institute (AISI 1996) Specification and the Australian/New Zealand Standard (AS/NZS 4600-1996) for cold-formed steel structures are formulated based on the results of experimental tests obtained by Winter & Pian (1946), Zetlin (1955), and Hetrakul & Yu (1978).

An important point to note is that the majority of the tests performed by the aforementioned authors are limited to the two basic types of sections depicted in Fig. 1. The section shown in Fig. 1a has a pair of flat single unreinforced webs (webs without stiffeners) with one stiffened flange and one unstiffened flange, while that shown in Fig. 1b has a degree of restraint against rotation of the web. However, in practice the design recommendations contained in the AISI Specification are also applied to other types of cross-sections such as unlipped channels which

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have a flat unstiffened web as well as two unstiffened flanges. The design equations for channels, Z-sections and hat sections are based on the experimental tests on hat sections illustrated in Fig. 1a, while those for I-sections or similar sections are based on the test results of the channel back-to-back sections illustrated in Fig. 1b. Furthermore, the specimens tested by Winter & Pian (1946), Zetlin (1955), and Hetrakul & Yu (1978) were thin gauge members (< 3 mm) having yield stresses less than 379 MPa (55 ksi). This is due to the limitation of cold-forming technology in the past. On the other hand, high strength steels and thicker sections can now be cold-formed (up to 8 mm).

In the present work, the appropriateness of the design equations specified in the AISI Specification for unlipped channel sections is investigated. For this purpose, a series of tests was carried out under four loading conditions as specified in the AISI Specification, namely EOF, IOF, ETF and ITF. Tests were performed on thin (1.47 mm) as well as thicker sections (> 3 mm) with yield stresses ranging from 275 to 550 MPa. The test results are compared with the AISI Specification and the AS/NZS 4600 Standard. Based on the results of the present experimental tests, a plastic mechanism model is proposed for web crippling strength of unlipped channels with stockier webs.

2 EXPERIMENTAL INVESTIGATION

2.1 Test Specimens and Bearing Plates

Three series of cold-formed unlipped channels were tested. Series S1 and S2 were rolled from structural steel sheets having nominal yield stresses of 300 MPa and 250 MPa respectively, while Series S3 were brake-pressed from zinc-coated structural steel sheets having a nominal yield stress of 450 MPa. The Series S1 sections (called Duragal) have in-line galvanising which increases their effective yield stress to 450 MPa when combined with roll-forming. Series S1 and S2 consisted of six different section sizes, having the nominal thicknesses of 4 mm and 5 mm, the nominal depth of the webs ranged from 80 mm to 200 mm, and the nominal flange widths ranged from 40 mm to 75 mm. Series S3 consisted of two different section sizes, having a nominal thickness of 1.5 mm, a nominal depth of the web of 96 mm, and a nominal flange width of either 36 mm or 48 mm. The web slenderness (h/t) values were 28.5, 38.3 for Series S1, 16.2, 16.9, 32.0, 34.6 for Series S2 and 60.9, 62.7 for Series S3. Hence, the Series S1 and S2 specimens had stocky webs whereas the Series S3 sections were more slender.

The specimen lengths were determined according to the AISI Specification and the AS/NZS 4600 Standard. Generally, the clear distance between opposed loads was set to be 1.5 times the overall depth of the web rather than 1.5 times the depth of the flat portion of the web, the latter being the minimum specified in the specifications. Tables 1, 2 and 3 show the measured test specimen dimensions for Series S1, S2 and S3 respectively, using the nomenclature defined in Fig. 2.

The load or reaction forces were applied by means of bearing plates. The bearing plates were fabricated using high strength steel having a nominal yield stress of 690 MPa. All bearing plates were designed to act across the full flange widths of the channels excluding the rounded corner. The length of bearing (N) was generally chosen to be the flange width of the channel for all series, although other bearing lengths were also used for Series S1 and S3.

2.2 Specimen Labelling

In Tables 1, 2 and 3, the specimens were labelled such that the series, loading conditions, the depth of the web and length of bearing could be identified from the label. For example, the label "S1EOF125N65-a" and "S1ITF125N65(2)" define the following specimens:

- The first two letters indicate that the specimen belongs to test Series S1.
- The third through the fifth letters indicate that the loading condition End-One-Flange (EOF) or Interior-Two-Flange (ITF) was used in the test.
- The next three digits (125) are the overall depth of the web in mm (125 mm).
- The notation "N65" indicates the length of bearing in mm (65 mm).
- The last letter "a" indicates that a pair of specimens ("a" and "b") was used in the test. A pair of specimens was used only in the EOF and IOF loadings.
- If a test was repeated, then "(1)" indicates the first test and "(2)" indicates the second test.

2.3 Material Properties

The material properties of each series of specimens were determined by tensile coupon tests. The coupons were taken from the centre of the web plate of the finished specimens. The tensile coupons were prepared and tested according to the Australian Standard AS1391 (1991) using 12.5 mm wide coupons of gauge length 50 mm. All the coupons were tested in a 300 kN capacity MTS displacement controlled testing machine using friction grips. A calibrated extensometer of 50 mm gauge length was used to measure the longitudinal strain. A data acquisition system was used to record the load and the gauge length extensions at regular intervals during the tests. The static load was obtained by pausing the applied straining for one minute near the 0.2% tensile proof stresses and the ultimate tensile strength.

Table 4 summarises the material properties determined from the coupon tests, namely the nominal and the measured static 0.2% tensile proof stress ($\sigma_{0.2}$), the static tensile strength (σ_u) and the elongation after fracture (ε_u) based on a gauge length of 50 mm. The 0.2% proof stresses were used as the corresponding yield stresses.

2.4 Loading Conditions and Test Rig

The channel specimens were tested using the four loading conditions according to the AISI Specification. These loading conditions are EOF, IOF, ETF and ITF, as shown in Figs 3a, 4a, 5a and 6a respectively.

For EOF loading, two channel specimens were used in the test to provide symmetric loading, and the specimens were bolted together at the central loading point. Two identical bearing plates of the same width were positioned at both ends of the specimens. The test arrangement is shown in Figs 3b and 3c for the front and end views of the test respectively. Hinge and roller supports were simulated by half rounds and teflon pads. Transducers were used to record the web deformations of the specimens so that deformations were taken between the bearing plates and the top of the specimens.

For IOF loading, two specimens were bolted together at the end supports, and a bearing plate was positioned at the mid-length of the specimens, as shown in Figs 4b and 4c for the front and end views of the test respectively. Photographs of the IOF loading are shown in Figs 7a and 7b for the front and end views respectively. Hinge and roller supports were also simulated by half rounds and teflon pads. The web deformations were measured between the bearing plate and the bottom of the specimens.

For ETF and ITF loadings, two identical bearing plates of the same width were positioned at the end and mid-length of each specimen respectively. Figs 5b, 5c, 6b and 6c show the front and end views of the tests. Photographs of the ETF loading are shown in Figs 8a and 8b for the front and end views respectively. Hinge supports were simulated by two half rounds in the line of action of the force. Web deformations of the specimen were obtained by the average of three transducers. The deformations were measured between the bearing plates. For ETF and ITF loadings, only one channel specimen was used in the test, as shown in 5c and 6c respectively, since the loads were always in the line of action of the force. For Series S3, specimens were only tested using the ETF and ITF loading conditions.

A 2000 kN capacity DARTEC servo-controlled hydraulic testing machine was used to apply a compressive force to the test specimens. Displacement control was used to drive the hydraulic actuator at a constant speed of 0.8 mm/min. A SPECTRA data acquisition system was used to record the load and the transducer readings at regular intervals during the tests. The static load was recorded by pausing for one minute near the ultimate load. This allows the stress relaxation associated with plastic straining to take place.

2.5 Test Results

The experimental ultimate web crippling loads per web (P_{Exp}) are given in Table 1, 2 and 3 for Series S1, S2 and S3 respectively. Three tests were repeated and these specimens are S1ITF125N65, S1ITF125N32.5 and S2IOF80N40 for Series S1 and S2. The test results for the repeated tests are very close to their first test values, with a maximum difference of 1.5%.

3 DESIGN RULES

The design rules to determine the web crippling strength of flexural members subjected to concentrated loads or reaction forces in the AISI Specification and the AS/NZS 4600 Standard for cold-formed steel structures are summarised in this section. The AS/NZS 4600 Standard has adopted the web crippling design rules from the AISI Specification, and no changes are introduced into the web crippling strength rules (Section C3.4 of the AISI Specification), except that the provision for using high strength steels with a yield stress greater than 459 MPa (66.5 ksi) in equations C3.4-1, C3.4-2 and C3.4-6 has not yet been adopted in the AS/NZS 4600 Standard.

The nominal web crippling strength (P_n) of channel sections calculated according to Section C3.4 of the AISI Specification is as follow,

<u>EOF Loading Condition (Eq. C3.4-2)</u>

$$P_n = t^2 k C_3 C_4 C_9 C_\theta \left[217 - 0.28\left(\frac{h}{t}\right)\right]\left[1 + 0.01\left(\frac{N}{t}\right)\right]^* \qquad (1)$$

* When yield stress ≥ 459 MPa (66.5 ksi), the value of kC_3 shall be taken as 1.34.
If $N/t > 60$, the factor [1 + 0.01(N/t)] may be increased to [0.71 + 0.015(N/t)].

IOF Loading Condition (Eq. C3.4-4)

$$P_n = t^2 k C_1 C_2 C_9 C_\theta \left[538 - 0.74\left(\frac{h}{t}\right)\right]\left[1 + 0.007\left(\frac{N}{t}\right)\right] \tag{2}$$

If $N/t > 60$, the factor [1 + 0.007(N/t)] may be increased to [0.75 + 0.011(N/t)].

ETF Loading Condition (Eq. C3.4-6)

$$P_n = t^2 k C_3 C_4 C_9 C_\theta \left[244 - 0.57\left(\frac{h}{t}\right)\right]\left[1 + 0.01\left(\frac{N}{t}\right)\right]^* \tag{3}$$

* When yield stress ≥ 459 MPa (66.5 ksi), the value of kC_3 shall be taken as 1.34.

ITF Loading Condition (Eq. C3.4-8)

$$P_n = t^2 k C_1 C_2 C_9 C_\theta \left[771 - 2.26\left(\frac{h}{t}\right)\right]\left[1 + 0.0013\left(\frac{N}{t}\right)\right] \tag{4}$$

In the design equations (1-4),

$$C_1 = 1.22 - 0.22k \tag{5}$$

$$C_2 = \left(1.06 - \frac{0.06 r_i}{t}\right) \le 1.0 \tag{6}$$

$$C_3 = 1.33 - 0.33k \tag{7}$$

$$C_4 = \left(1.15 - \frac{0.15 r_i}{t}\right) \le 1.0 \quad \text{but not less than 0.5} \tag{8}$$

$$C_9 = \begin{cases} 1.0 & \text{for U.S. customary units} \\ 6.9 & \text{for metric units} \end{cases} \tag{9}$$

$$C_\theta = 0.7 + 0.3\left(\frac{\theta}{90}\right)^2 \tag{10}$$

$$k = \frac{894 f_y}{E} \tag{11}$$

where t is the thickness of the web, h is the depth of the flat portion of the web measured along the plane of the web, N is the length of the bearing, r_i is the inside corner radius, C_1 to C_9 and

C_θ are the coefficient, θ is the angle between the plane of the web and the plane of the bearing surface, k is the non-dimensional yield stress, f_y is the yield stress and E is the Young's modulus of elasticity. The limits of the above mentioned equations for channel sections are $h/t \leq 200$, $r_i/t \leq 6$ (for beams), $N/t \leq 210$, $N/h \leq 3.5$ and $45° \leq \theta \leq 90°$. The test specimens for all three series satisfied these limits.

As mentioned in the commentary of the AISI Specification (1996), the provisions for web crippling strength were previously developed on the basis of the experimental investigations using steels having yield stress less than 379 MPa (55 ksi) (Hetrakul and Yu 1978). For equations C3.4-1, C3.4-2 and C3.4-6 of the Specification, it can be shown that the web crippling strength for a given section increases as the yield stress increases only up to 459 MPa (66.5 ksi), beyond which the strength decreases as the yield stress increases. Therefore, these equations are applicable only for yield stress less than 459 MPa (66.5 ksi), as stated in the Specification. In order not to penalise the use of high strength steels, the AISI Specification temporary conservatively specified that a constant value of $kC_3 = 1.34$ is used in the equations when the yield stress is greater than or equal to 459 MPa (66.5 ksi).

For Series S3, the yield stresses of the channel specimens are greater than 459 MPa and the current design strength (P_n) predicted by the AISI Specifications and the AS/NZS 4600 Standard are shown in Table 7a. The used of a constant value of $kC_3 = 1.34$ in calculating the design strength provided similar results to the AS/NZS 4600 Standard (without the use of the constant value), with a maximum difference of 4.3%.

4 COMPARISON OF TEST STRENGTHS WITH CURRENT DESIGN STRENGTHS

The web crippling loads per web obtained from the tests are compared with the nominal web crippling strengths predicted using the current AISI Specification and the AS/NZS 4600 Standard for cold-formed steel structures. Tables 5a, 6a and 7a show the comparison of the test strengths (P_{Exp}) with the unfactored design strengths (P_n) for Series S1, S2 and S3 respectively. The design strengths were calculated using the average measured cross-section dimensions and the measured material properties as detailed in Tables 1-3 and 4 respectively. A value of 203,000 MPa was used for the Young's modulus of elasticity (E) in calculating the design strength.

The current design strength (P_n) predicted by the specifications are unconservative, except that the specifications closely predicted the web crippling strength of the EOF loading condition for Series S1 and S2. For Series S1, on average, the web crippling strength of a specimen subjected to either IOF or ETF loading condition was reached in the test at 72% of the value predicted by the current specifications, as shown in Table 5a. For a specimen (in the same series) subjected to the ITF loading condition, the corresponding value is 60%. Similar situations were encountered with Series S2 and S3, the details of which are tabulated in Tables 6a and 7a respectively. It is noteworthy that a test strength as low as 37% of the design strength was obtained in the test for a certain specimen (Series S2) subjected to the ITF loading condition.

The Series S3 specimens, which had a web slenderness h/t of 60.9 and 62.7 were more accurately predicted for the ETF and ITF loading conditions than the Series S1 and S2 specimens which had web slenderness values less than or equal to 38.3. It therefore appear that a lower h/t limit of, maybe, 60 should be applied to the AISI Specification and AS/NZS 4600 design equations at this stage.

5 PROPOSED DESIGN EQUATIONS

The nominal web crippling strength (P_n) of unlipped channels calculated according to the current design rules are unconservative, except for the EOF loading condition for Series S1 and S2, as shown in Table 5a, 6a and 7a. Hence, design equations for unlipped channels with stockier webs are proposed in this paper. It is assumed that the bearing load is applied eccentrically to the web due to the presence of the corner radii as shown in Fig. 9, which produces bending of the web out of its plane causing a plastic mechanism as shown in Fig. 9. A plastic mechanism model has been used to establish design formulae, which account for the eccentric loading of the web. The approach is similar that used for square and rectangular hollow sections (SHS and RHS) by Zhao and Hancock (1992 and 1995) to determine the web crippling strengths for both interior and end bearing loads. The Zhao and Hancock SHS and RHS sections also had stockier webs than is intended for the AISI and AS/NZS 4600 web crippling equations.

The proposed formulae for channel sections are summarised as:

$$P_{pm} = \frac{M_p N_m}{r} \tag{12}$$

where

$$M_p = \frac{f_y t^2}{4} \tag{13}$$

$$r = r_i + \frac{t}{2} \tag{14}$$

$$N_m = \begin{cases} N + id & \text{for Interior Loading} \\ N + \dfrac{ed}{2} & \text{for End Loading} \end{cases} \tag{15}$$

in which, P_{pm} is the web crippling strength predicted by using the plastic mechanism model, M_p is the plastic moment per unit length, r and r_i are the centreline and inside corner radii respectively, t is the thickness of the web, f_y is the yield stress, d is the overall depth of the web and N is the length of the bearing. In equation 15, N_m is the assumed mechanism length, as shown in Fig. 10a and 10b for interior and end loading respectively. It is based on an assumption that the dispersion slope of the load through the corner and the web is 1:1 with correction factors i and e for interior and end loading respectively. The correction factors for interior loading are i = 1.2 and 1.3 for IOF and ITF respectively, and the correction factors for end loading are e = 1 and 0.6 for EOF and ETF respectively.

6 COMPARISON OF TEST STRENGTHS WITH PROPOSED DESIGN STRENGTHS

The experimental ultimate web crippling loads per web (P_{Exp}) obtained for the Series S1, S2 and S3 are compared in Tables 5b, 6b and 7b with the proposed design strengths (P_{pm}) using the plastic mechanism model. The proposed design strengths were calculated using the average measured cross-section dimensions and the measured material properties as detailed in Tables 1-3 and 4 respectively.

The proposed design strengths (P_{pm}) are generally conservative for the Series S1 and S2 specimens and unconservative for the Series S3 specimens probably because buckling controls. The plastic mechanism model approach therefore appear to be suitable for unlipped channels with a web slenderness (h/t) less than 40 but inaccurate for more slender webs where a web buckling model should be included.

7 CONCLUSIONS

A test program on the web crippling behaviour of cold-formed unlipped channels has been presented. Channels having nominal yield stresses of 450 MPa and 250 MPa as well as different plate slenderness of the web were tested. The channel specimens were tested using the four loading conditions (EOF, IOF, ETF and ITF) according to the AISI Specification. The web slenderness values ranged from 16.2 to 62.7.

The test strengths were compared with the current design strength obtained using the American (1996) Specification and the Australian/New Zealand Standard (1996) for cold-formed steel structures. It is demonstrated that the current design strengths predicted by the specifications are unconservative for unlipped channels, particularly those with web slenderness less than 40. In some cases involving the EOF loading condition, the specifications closely predicted the web crippling strength. For a certain specimen subjected to ITF loading condition the test strength is only 37% of the design strength predicted by the current specifications.

Web crippling design equations for unlipped channels based on a plastic mechanism model have been proposed. It is shown that the proposed design strengths are generally conservative for unlipped channels with a web slenderness less than 40 but unconservative for those with a web slenderness of approximately 60. It is suggested that the web crippling design equations in the AISI Specification and the AS/NZS 4600 Standard be limited to web slenderness values greater than 60 when applied to unlipped channels. Further investigation is required in the web slenderness range 40 to 60.

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NOTATION

b_f	Overall width of flange
C_1 to C_9	Web crippling coefficients
C_θ	Web crippling coefficient
d	Overall depth of web
E	Young's modulus of elasticity
e	Correction factor for end loading condition
f_y	Yield stress
h	Depth of flat portion of web measured along the plane of web
i	Correction factor for interior loading condition
k	Non-dimensional yield stress
L	Actual length of test specimen
M_p	Plastic moment per unit length
N	Length of bearing
N_m	Assumed mechanism length

P_{Exp}	Experimental ultimate web crippling load per web
P_n	Nominal web crippling strength obtained from specifications
P_{pm}	Proposed web crippling strength predicted by using plastic mechanism model
r	Centreline corner radius of specimen
r_i	Inside corner radius of specimen
t	Thickness of channel section
x	In-plane transverse coordinate
y	Out-of-plane transverse coordinate
ε_u	Elongation (tensile strain) after fracture based on a gauge length of 50mm
θ	Angle between the plane of the web and the plane of the bearing surface
$\sigma_{0.2}$	Static 0.2% tensile proof stress
σ_u	Static ultimate tensile strength

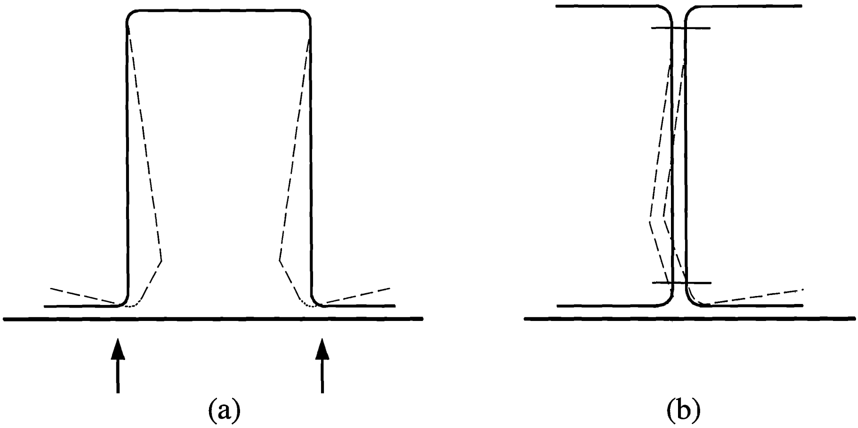


Fig. 1. Web crippling of beams

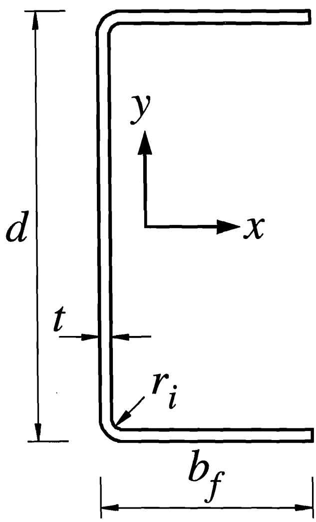
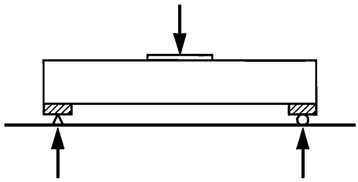
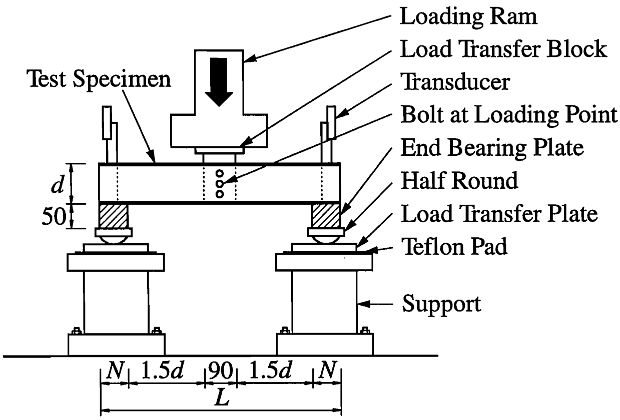


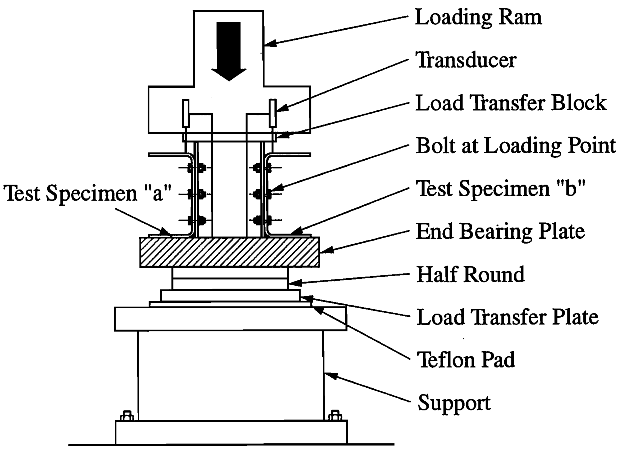
Fig. 2. Definition of symbols



(a) EOF Loading



(b) Front view



(c) End view

Fig. 3. Schematic view of the End-One-Flange (EOF) test arrangement

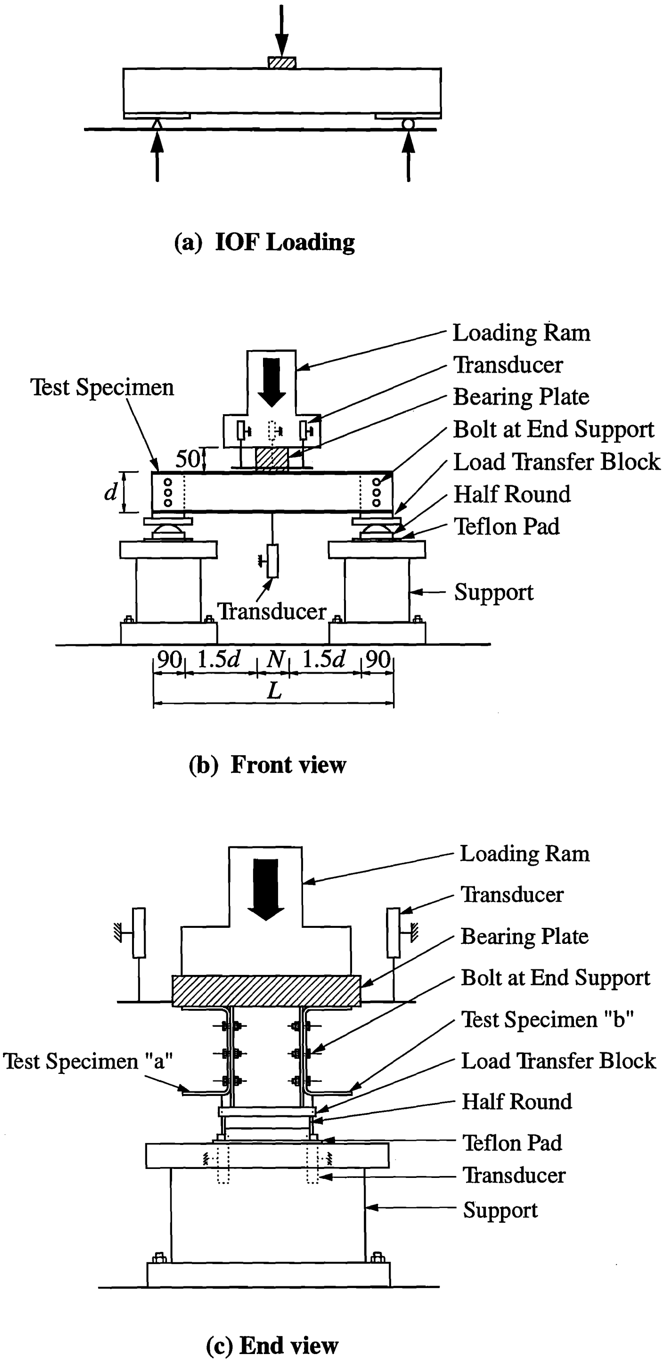
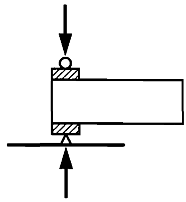
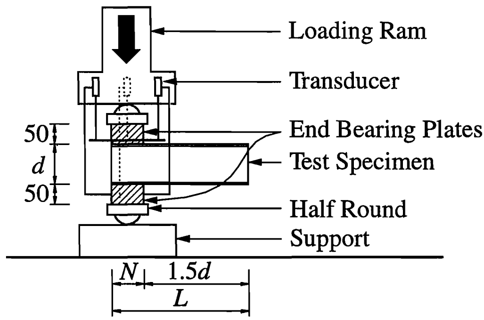


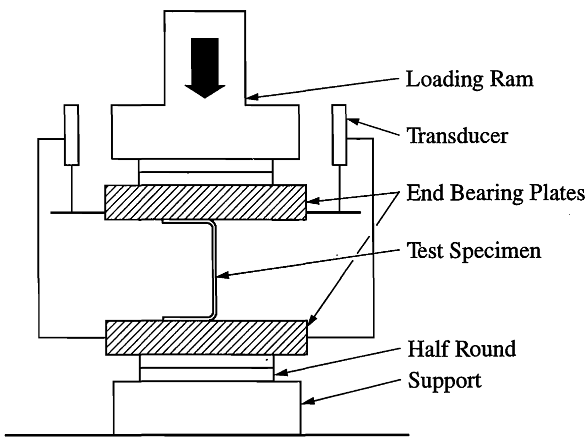
Fig. 4. Schematic view of the Interior-One-Flange (IOF) test arrangement



(a) **ETF Loading**

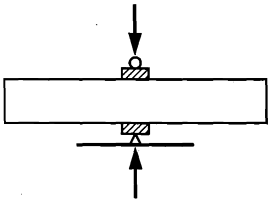


(b) **Front view**

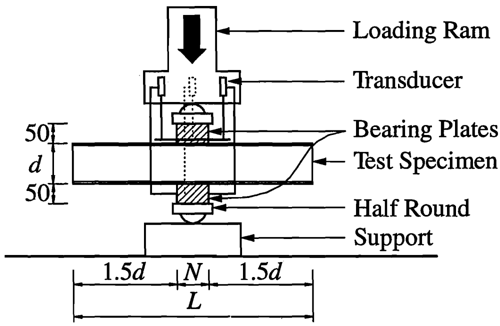


(c) **End view**

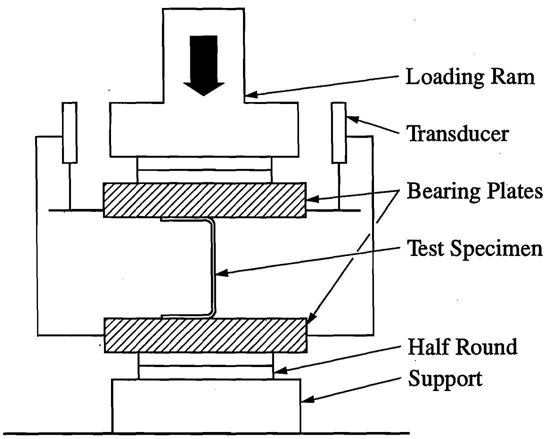
Fig. 5. Schematic view of the End-Two-Flange (ETF) test arrangement



(a) ITF Loading

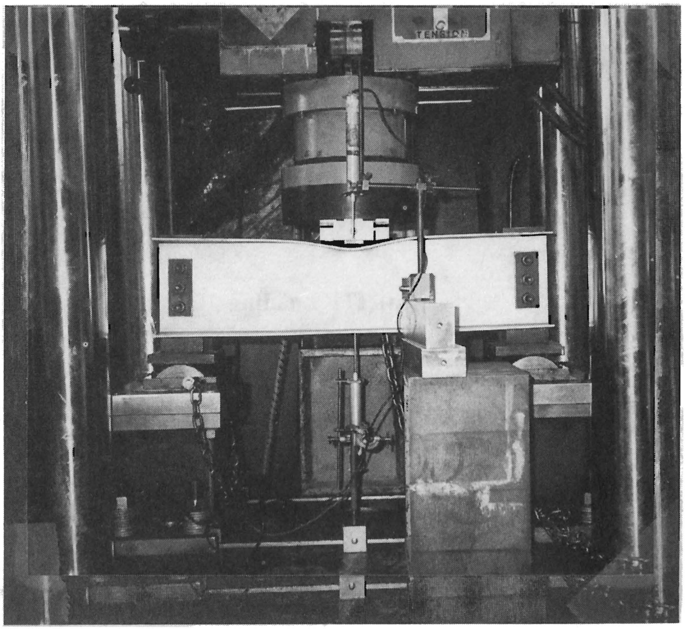


(b) Front view

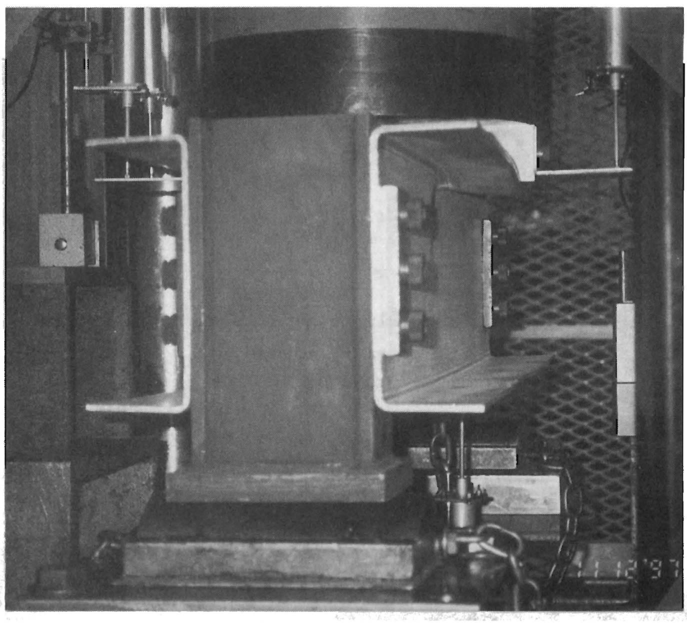


(c) End view

Fig. 6. Schematic view of the Interior-Two-Flange (ITF) test arrangement

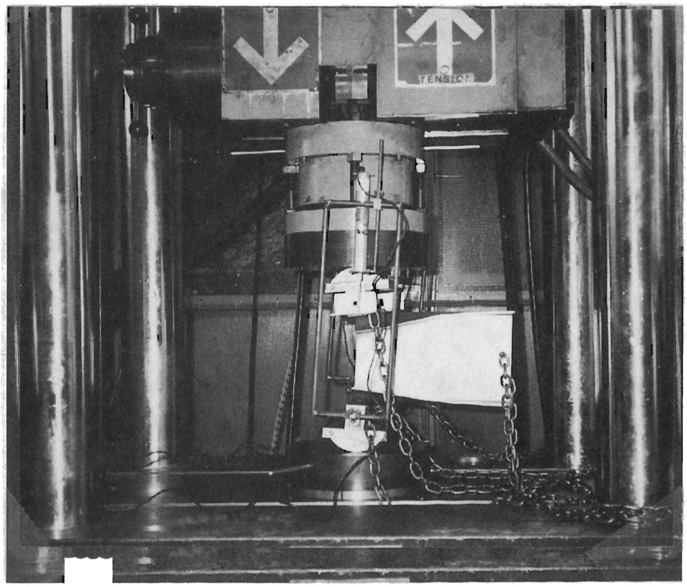


(a) Front view

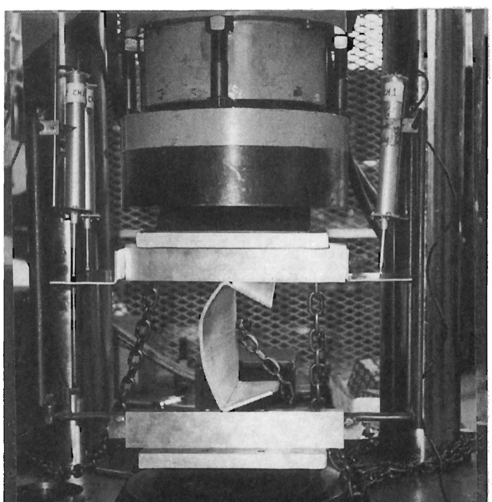


(b) End view

Fig. 7. Interior-One-Flange (IOF) Test setup

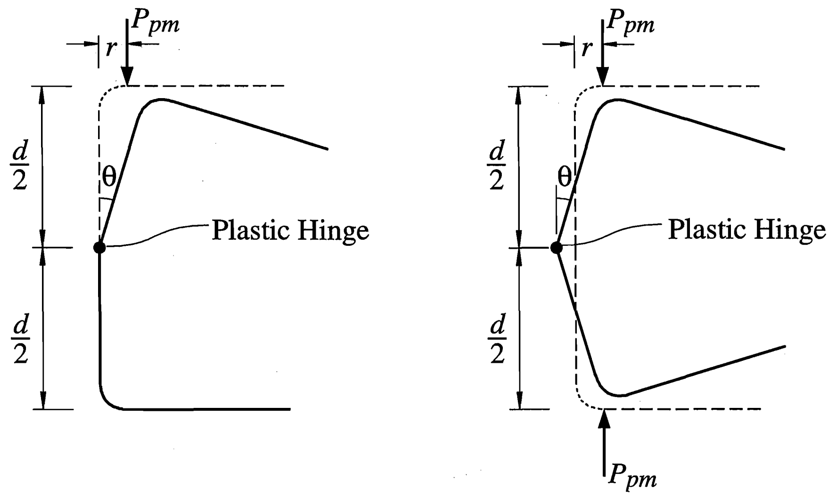


(a) Front view



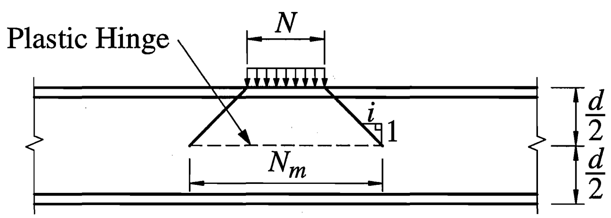
(b) End view

Fig. 8. End-Two-Flange (ETF) Test setup

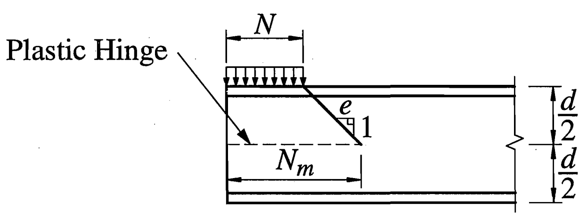


(a) One flange loading (EOF & IOF) **(b) Two flange loading (ETF & ITF)**

Fig. 9. Mechanism model



(a) Interior loading



(b) End loading

Fig. 10. Assumed plastic hinge position and mechanism length, N_m

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S1EOF125N65-a	125.0	65.5	3.85	3.9	594.0	35.3
S1EOF125N65-b	124.9	65.5	3.84	3.9	593.4	35.3
S1EOF125N32.5-a	125.6	65.7	3.84	3.9	528.8	29.7
S1EOF125N32.5-b	125.4	65.6	3.84	3.9	529.2	29.7
S1IOF125N65-a	125.0	65.7	3.86	3.9	618.5	63.6
S1IOF125N65-b	125.0	65.6	3.86	3.9	619.3	63.6
S1IOF125N32.5-a	125.0	65.5	3.86	3.9	587.0	57.4
S1IOF125N32.5-b	125.0	65.7	3.86	3.9	586.8	57.4
S1ETF125N65	125.6	65.4	3.83	3.9	252.5	28.2
S1ETF125N32.5	125.3	65.3	3.84	3.9	219.8	23.4
S1ITF125N65(1)	125.0	65.6	3.84	3.9	440.0	60.4
S1ITF125N65(2)	124.9	65.5	3.84	3.9	440.1	59.6
S1ITF125N32.5(1)	125.1	65.6	3.85	3.9	407.7	64.4
S1ITF125N32.5(2)	124.9	65.3	3.85	3.9	407.5	63.8
Mean	125.1	65.5	3.85	3.9		
S.D.	0.25	0.13	0.01	0.00		
Note: 1 in. = 25.4mm; 1 kip = 4.45 kN						

(a) Channel 125×65×4

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S1EOF200N75-a	198.7	75.8	4.71	4.2	839.8	49.3
S1EOF200N75-b	198.8	75.8	4.71	4.2	839.5	49.3
S1EOF200N37.5-a	198.8	76.0	4.72	4.2	764.6	43.7
S1EOF200N37.5-b	198.8	75.8	4.74	4.2	764.5	43.7
S1IOF200N75-a	198.9	75.9	4.74	4.2	855.2	94.5
S1IOF200N75-b	198.7	75.9	4.73	4.2	854.2	94.5
S1IOF200N37.5-a	198.7	75.9	4.72	4.2	816.8	91.2
S1IOF200N37.5-b	198.8	75.9	4.74	4.2	817.5	91.2
S1ETF200N75	198.9	75.9	4.72	4.2	375.3	40.2
S1ETF200N37.5	198.7	75.9	4.72	4.2	336.9	31.2
S1ITF200N75	198.7	75.9	4.72	4.2	675.2	100.1
S1ITF200N37.5	198.8	76.0	4.73	4.2	638.0	99.8
Mean	198.8	75.9	4.73	4.2		
S.D.	0.08	0.07	0.01	0.00		
Note: 1 in. = 25.4mm; 1 kip = 4.45 kN						

(b) Channel 200×75×5

Table 1. Measured specimen dimensions and experimental ultimate loads for Series S1

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S2EOF80N40-a	80.2	39.7	3.82	4.0	320.0	26.4
S2EOF80N40-b	80.3	39.6	3.85	4.0	320.0	26.4
S2IOF80N40-a(1)	80.3	39.7	3.85	4.0	369.8	43.9
S2IOF80N40-b(1)	80.3	39.7	3.81	4.0	368.7	43.9
S2IOF80N40-a(2)	80.3	39.6	3.84	4.0	370.0	44.2
S2IOF80N40-b(2)	80.2	39.7	3.82	4.0	369.0	44.2
S2ETF80N40	80.2	39.7	3.85	4.0	159.8	14.8
S2ITF80N40	80.3	39.7	3.78	4.0	280.4	32.4
Mean	80.3	39.7	3.83	4.0		
S.D.	0.05	0.05	0.02	0.00		

Note: 1 in. = 25.4mm; 1 kip = 4.45 kN

(a) Channel 80×40×4

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S2ETF100N50	99.7	49.9	4.83	5.8	201.0	26.7
S2ITF100N50	99.7	49.9	4.82	5.8	352.3	56.9
Mean	99.7	49.9	4.83	5.8		
S.D.	0.00	0.00	0.01	0.00		

Note: 1 in. = 25.4mm; 1 kip = 4.45 kN

(b) Channel 100×50×5

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S2EOF140N50-a	139.9	49.6	3.87	4.0	518.0	27.9
S2EOF140N50-b	139.8	49.9	3.87	4.0	517.5	27.9
S2IOF140N50-a	140.0	49.9	3.89	4.0	559.4	49.7
S2IOF140N50-b	140.0	49.8	3.90	4.0	559.0	49.7
S2ETF140N50	139.9	49.9	3.88	4.0	261.7	18.7
S2ITF140N50	140.0	50.2	3.89	4.0	471.5	44.3
Mean	139.9	49.9	3.88	4.0		
S.D.	0.08	0.19	0.01	0.00		

Note: 1 in. = 25.4mm; 1 kip = 4.45 kN

(c) Channel 140×50×4

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S2EOF150N75-a	149.4	75.4	3.86	4.0	559.2	33.2
S2EOF150N75-b	149.3	75.4	3.86	4.0	600.0	33.2
S2IOF150N75-a	149.3	75.7	3.85	4.0	614.5	55.1
S2IOF150N75-b	149.2	75.5	3.85	4.0	615.5	55.1
S2ETF150N75	149.3	75.3	3.86	4.0	303.8	19.0
S2ITF150N75	149.2	75.6	3.86	4.0	526.9	43.6
Mean	149.3	75.5	3.86	4.0		
S.D.	0.08	0.15	0.01	0.00		

Note: 1 in. = 25.4mm; 1 kip = 4.45 kN

(d) Channel 150×75×4

Table 2. Measured specimen dimensions and experimental ultimate loads for Series S2

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S3ETF96N75	94.2	49.9	1.47	0.85	221.6	5.4
S3ETF96N50	94.4	49.8	1.47	0.85	196.1	4.8
S3ITF96N75	94.2	49.9	1.47	0.85	366.1	14.2
S3ITF96N50	93.8	50.1	1.46	0.85	340.1	13.1
Mean	94.2	49.9	1.47	0.85		
S.D.	0.25	0.13	0.01	0.00		
Note: 1 in. = 25.4mm; 1 kip = 4.45 kN						

(a) Channel 96×48×1.5

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
S3ETF96N37.5	96.5	36.8	1.47	0.85	184.0	4.3
S3ETF96N25	97.0	36.8	1.47	0.85	170.0	3.8
S3ITF96N37.5	97.2	36.9	1.47	0.85	329.6	12.5
S3ITF96N25	96.4	36.9	1.47	0.85	313.7	12.3
Mean	96.8	36.9	1.47	0.85		
S.D.	0.39	0.06	0.00	0.00		
Note: 1 in. = 25.4mm; 1 kip = 4.45 kN						

(b) Channel 96×36×1.5

Table 3. Measured specimen dimensions and experimental ultimate loads for Series S3

Test Series	Channel	Nominal	Measured		
	$d \times b_f \times t$	$\sigma_{0.2}$	$\sigma_{0.2}$	σ_u	ε_u
		(MPa)	(MPa)	(MPa)	(%)
S1	125×65×4	450	405	510	23
S1	200×75×5	450	415	520	24
S2	80×40×4	250	280	370	35
S2	100×50×5	250	295	370	36
S2	140×50×4	250	290	380	39
S2	150×75×4	250	275	375	37
S3	96×48×1.5	450	510	540	11
S3	96×36×1.5	450	550	570	10
Note: 1 ksi = 6.89 MPa					

Table 4. Nominal and measured material properties

Channel	Measured					Exp. Load per Web				AISI & AS/NZS 4600				Comparison			
	Bearing Length	0.2% Proof Stress	Ratio			P_{Exp}				P_n				$\frac{P_{Exp}}{P_n}$			
$d \times b_f \times t$	N	$\sigma_{0.2}$	h/t	r_i/t	N/t	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF
	(mm)	(MPa)				(kN)				(kN)							
125×65×4	65.0	405	28.5	1.01	16.9	35.3	63.6	28.2	60.4 59.6#	33.0	87.2	35.9	108.9	1.07	0.73	0.79	0.55
125×65×4	32.5	405	28.5	1.01	8.4	29.7	57.4	23.4	64.4 63.8#	30.6	82.6	33.3	107.8	0.97	0.69	0.70	0.60
200×75×5	75.0	415	38.3	0.89	15.9	49.3	94.5	40.2	100.1	49.0	130.7	52.8	161.2	1.01	0.72	0.76	0.62
200×75×5	37.5	415	38.3	0.89	7.9	43.7	91.2	31.2	99.8	45.7	124.1	49.2	159.6	0.96	0.73	0.63	0.63
													Mean	1.00	0.72	0.72	0.60

Second test

Note: 1 in. = 25.4mm; 1 ksi = 6.89 MPa; 1 kip = 4.45 kN

(a) Current design strength

Channel	Measured					Exp. Load per Web				Proposed Design Strength				Comparison			
	Bearing Length	0.2% Proof Stress	Ratio			P_{Exp}				P_{pm}				$\frac{P_{Exp}}{P_{pm}}$			
$d \times b_f \times t$	N	$\sigma_{0.2}$	h/t	r_i/t	N/t	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF
	(mm)	(MPa)				(kN)				(kN)							
125×65×4	65.0	405	28.5	1.01	16.9	35.3	63.6	28.2	60.4 59.6#	32.9	55.4	26.4	58.6	1.07	1.15	1.07	1.03
125×65×4	32.5	405	28.5	1.01	8.4	29.7	57.4	23.4	64.4 63.8#	24.5	47.1	18.0	50.3	1.21	1.22	1.30	1.28
200×75×5	75.0	415	38.3	0.89	15.9	49.3	94.5	40.2	100.1	61.7	110.9	47.6	117.9	0.80	0.85	0.84	0.85
200×75×5	37.5	415	38.3	0.89	7.9	43.7	91.2	31.2	99.8	48.4	97.6	34.3	104.6	0.90	0.93	0.91	0.95
													Mean	1.00	1.04	1.03	1.03

Second test

Note: 1 in. = 25.4mm; 1 ksi = 6.89 MPa; 1 kip = 4.45 kN

(b) Proposed design strength

Table 5. Comparison of web crippling test strengths with current and proposed design strengths for Series S1

Channel	Measured					Exp. Load per Web				AISI & AS/NZS 4600				Comparison			
	Bearing Length	0.2% Proof Stress	Ratio			P_{Exp}				P_n				$\frac{P_{Exp}}{P_n}$			
$d \times b_f \times t$	N	$\sigma_{0.2}$	h/t	r_i/t	N/t	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF
	(mm)	(MPa)				(kN)				(kN)							
80×40×4	40.0	280	16.9	1.04	10.4	26.4	43.9 44.2#	14.8	32.4	26.8	66.6	29.6	87.7	0.99	0.66	0.50	0.37
100×50×5	50.0	295	16.2	1.20	10.4	-------	-------	26.7	56.9	42.9	108.9	47.4	143.6	-------	-------	0.56	0.40
140×50×4	50.0	290	32.0	1.03	12.9	27.9	49.7	18.7	44.3	28.2	69.7	30.6	88.3	0.99	0.71	0.61	0.50
150×75×4	75.0	275	34.6	1.04	19.4	33.2	55.1	19.0	43.6	28.5	69.0	30.9	84.1	1.16	0.80	0.61	0.52
													Mean	1.05	0.72	0.57	0.45

Second test

Note: 1 in. = 25.4mm; 1 ksi = 6.89 MPa; 1 kip = 4.45 kN

(a) Current design strength

Channel	Measured					Exp. Load per Web				Proposed Design Strength				Comparison			
	Bearing Length	0.2% Proof Stress	Ratio			P_{Exp}				P_{pm}				$\frac{P_{Exp}}{P_{pm}}$			
$d \times b_f \times t$	N	$\sigma_{0.2}$	h/t	r_i/t	N/t	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF	EOF	IOF	ETF	ITF
	(mm)	(MPa)				(kN)				(kN)							
80×40×4	40.0	280	16.9	1.04	10.4	26.4	43.9 44.2#	14.8	32.4	13.9	23.7	11.1	25.1	1.90	1.85	1.33	1.29
100×50×5	50.0	295	16.2	1.20	10.4	-------	-------	26.7	56.9	20.9	35.5	16.7	37.6	-------	-------	1.60	1.51
140×50×4	50.0	290	32.0	1.03	12.9	27.9	49.7	18.7	44.3	22.0	40.0	16.9	42.6	1.27	1.24	1.11	1.04
150×75×4	75.0	275	34.6	1.04	19.4	33.2	55.1	19.0	43.6	25.9	43.9	20.7	46.5	1.28	1.26	0.92	0.94
													Mean	1.48	1.45	1.24	1.20

Second test

Note: 1 in. = 25.4mm; 1 ksi = 6.89 MPa; 1 kip = 4.45 kN

(b) Proposed design strength

Table 6. Comparison of web crippling test strengths with current and proposed design strengths for Series S2

Channel	Measured					Exp. Load per Web		AISI		AS/NZS 4600		Comparison AISI		Comparison AS/NZS 4600	
	Bearing Length	0.2% Proof Stress	Ratio			P_{Exp}		P_n		P_n		$\frac{P_{Exp}}{P_n}$		$\frac{P_{Exp}}{P_n}$	
$d \times b_f \times t$	N	$\sigma_{0.2}$	h/t	r_i/t	N/t	ETF	ITF	ETF	ITF	ETF	ITF	ETF*	ITF	ETF	ITF
	(mm)	(MPa)				(kN)		(kN)		(kN)					
96×48×1.5	75.0	510	60.9	0.58	51.0	5.4	14.2	6.3*	16.4	6.2	16.4	0.86*	0.87	0.87	0.87
96×48×1.5	50.0	510	60.9	0.58	34.0	4.8	13.1	5.6*	16.1	5.5	16.1	0.86*	0.81	0.87	0.81
96×36×1.5	37.5	550	62.7	0.58	25.5	4.3	12.5	5.2*	16.1	5.0	16.1	0.83*	0.78	0.86	0.78
96×36×1.5	25.0	550	62.7	0.58	17.0	3.8	12.3	4.9*	16.0	4.7	16.0	0.78*	0.77	0.81	0.77
											Mean	0.83*	0.81	0.85	0.81

* When yield stress ≥ 459 MPa (66.5 ksi), the value of $kC_3 = 1.34$.

Note: 1 in. = 25.4mm; 1 ksi = 6.89 MPa; 1 kip = 4.45 kN

(a) Current design strength

Channel	Measured					Exp. Load per Web		Proposed Design Strength		Comparison	
	Bearing Length	0.2% Proof Stress	Ratio			P_{Exp}		P_{pm}		$\frac{P_{Exp}}{P_{pm}}$	
$d \times b_f \times t$	N	$\sigma_{0.2}$	h/t	r_i/t	N/t	ETF	ITF	ETF	ITF	ETF	ITF
	(mm)	(MPa)				(kN)		(kN)			
96×48×1.5	75.0	510	60.9	0.58	51.0	5.4	14.2	17.9	34.3	0.30	0.41
96×48×1.5	50.0	510	60.9	0.58	34.0	4.8	13.1	13.6	30.0	0.35	0.44
96×36×1.5	37.5	550	62.7	0.58	25.5	4.3	12.5	12.5	30.6	0.34	0.41
96×36×1.5	25.0	550	62.7	0.58	17.0	3.8	12.3	10.1	28.3	0.38	0.43
									Mean	0.34	0.42

Note: 1 in. = 25.4mm; 1 ksi = 6.89 MPa; 1 kip = 4.45 kN

(b) Proposed design strength

Table 7. Comparison of web crippling test strengths with current and proposed design strengths for Series S3